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Introduction

In this paper [1] we describe the concept, and the basic scaling relation ships of solid state heat capacity lasers Intermediate between single shot and average power systems, the heat capacity concept scales solid state lasers to MW levels of burst power.

Single shot solid state lasers have had several decades of technical development, and their largest representatives are fusion lasers which deliver precisely shaped ns-duration pulses at MJ levels of energy to sub-millimeter targets [2] Their key purpose is to serve as a research tool for fusion, and single shot operation (i e no installed cooling) is plenty sufficient to meet shot repetition needs Average power solid state lasers [3] have experienced considerable development as well, but it is well known that the deposition and removal of waste heat in the solid state medium imposes a design constraint that has so far limited solid state lasers to several kW of average power Nevertheless, the widely recognized operational attractiveness of all solid state systems has continued to fuel the search for achieving ever higher powers with this specific technology

Heat capacity operation [4,5] is intermittent to single shot and steady state average power operation, in that single shots are rapidly added on time scales short compared to thermal diffusion times through the active medium. In this way, the buildup of thermal gradients is avoided and the device has the thermo-optical characteristics of a single shot device The waste heat generated during lasing is stored in the active medium, whose temperature rises from a chosen starting value to a temperature where lasing operation becomes inefficient. At that point lasing is stopped and the active medium is re-set to its starting temperature by cooling, so that a new lasing sequence can begin again Lasing times of many seconds can be achieved, generating up to MW levels of burst power during this time. This burst operation makes the heat capacity laser concept clearly more suited to applications which require large amounts of energy (MJ-levels) but for short periods of time (several seconds) Like all lasers, the heat capacity laser also needs to be sized in terms of its output characteristics with a specific application in mind, and then optimized with respect to platform limits, cost, and so on

In principle, all solid state medium architectures (rods, slabs, disks) are amenable to heat capacity operation, but depending on how the beam samples the various instantaneous opto-mechanical gradients, some architectures are less favorable than others We are considering the Brewster's angle disk architecture, since it scales in power with area, and has its gradients essentially oriented along the beam, which is the most favored of all situations.

Key physics characteristics:

In the next section, we shall briefly outline the basic physics which underlies heat capacity laser operation, by going in more detail through one operational cycle, and using it to explore the respective operational limits of each issue. We begin lasing at a starting temperature, end lasing at an upper temperature and cool back down to the starting temperature.

Since we are operating a heat capacity based system, a larger temperature swing will provide for more energy output. A look at the functional dependence of heat capacity with temperature [6] shows that all solids have a heat capacity which is characterized by the Debye temperature, at which roughly 90% of the limiting value of the heat capacity is reached.

$$c_p = 3R\left(\frac{T_D}{T}\right)^2 \frac{e^{\frac{T_D}{T}}}{\left(e^{\frac{T_D}{T}}-1\right)^2} \qquad (1)$$

The Debye temperature of typical laser crystals (garnets) is about 750 K [7]. This results in the following observations.

For operation around room temperature, the heat capacity is still rising considerably versus temperature Therefore, heat capacity lasing will want to utilize preferably higher temperature ranges Optimized heat capacity lasers will always want to end at the highest possible temperature, and begin at as low a temperature as required to fulfill specifications

For starting temperatures lower than ~ 1/3 the Debye temperature, the added accessible heat capacity is small. Folded into this must be the practical recognition that the engineering overhead in terms of size, weight and complexity to achieve these lower temperatures becomes increasingly more burdensome as well. Therefore, below a practical starting temperature, more heat capacity will be derived from more mass, rather than from a larger temperature swing.

In a practical Nd^{3+} based heat capacity laser, these effects conspire to place a practical starting temperature in the neighborhood of 0 °C Other systems, however, like those operated in extremely cold environments, will naturally optimize at lower starting temperatures.

As lasing begins, waste heat is deposited in the active medium (see Fig. 1) At left, we see the temperature and stress profile of conventional, steady state average power solid state lasers The developing surface stress is tensile and develops as a result of the heat flow through the active medium. The situation in a heat capacity solid state laser is fundamentally different (Fig. 1, right). During the lasing phase, heat is now stored in the active medium. Because the exponential absorption profile deposits more energy near the surfaces, heat flow now occurs from the slab surfaces into the center of the active medium. This makes the surfaces hotter than the center, hence during the lasing phase, the surface stress is now compressive, not tensile. This eliminates what was a key restriction to power scaling in steady state average power lasers, and allows the heat capacity laser to be operated at far higher burst powers than a steady state system could ever be considered to function [1].

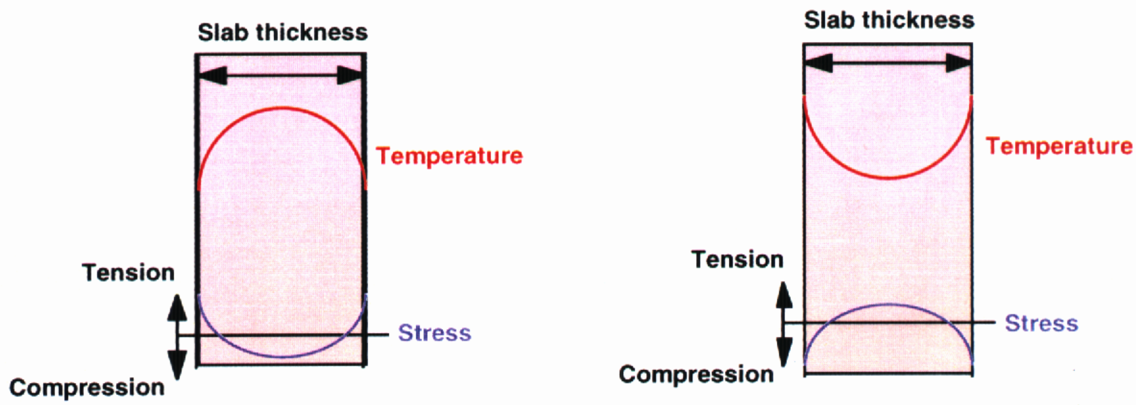


Fig.1. Left: Steady state average power operation Right: Heat capacity operation

Due to deposition of waste heat in the active medium, its temperature will continually rise. This makes it important to have a lasing process, which generates the most output energy per waste heat produced [1]. It is, however, misleading to conclude that this is synonymous with the lowest possible waste heat parameter, since a lasing ion whose lower level is too close to the ground state is obviously not capable of much lasing before the active medium heats up, i.e. store enough waste heat (see below). It is for this reason that ions like Yb^{3+}, when compared to Nd^{3+}, are fundamentally unsuited to heat capacity laser operation.

It is, however, important to have a pump source which generates the least amount of waste heat per pump photon. As much as flash lamps have been the workhorse for pumping solid state lasers for decades, they are unsuited for heat capacity operation, since their waste heat per inverted ion is just too large. Furthermore, since the heat capacity laser was described as a single shot device of high burst repetition rate, the repetition rate limit of flash lamps, especially when operated at a high explosion fraction, is a further drawback of this pump source. Diode array pumping [3] is far better suited, and it is the rapid technology development of this pump source that has helped move heat capacity lasers into the realm of practical interest. Further developments of these pump sources needs to aim not only for a reduction in the cost per watt of pump power,

but also in a reduction of parts count for large pump array areas, whilst maintaining as high a duty cycle as possible, since this provides a high repetition rate at a given pump pulse duration (~ 1/2 ms).
As the temperature of the active medium continues to increase, the point will be reached where the lower lasing level of the active ion will be thermally populated from the ground state according to the Boltzman factor $e^{-E/kT}$, where E is the energy of the lower laser level, and T is the instantaneous operating temperature of the heat capacity laser [8] This reduces the available gain for a given pump power in a way very familiar to those who operate Yb^{3+} or Er^{3+} at room temperature. For Nd^{3+}, this effect sets in around from about 100 °C to 150 °C , depending on the initial gain to loss ratio. In summary, an optimized, Nd^{3+} based, heat capacity laser will operate over temperature excursions of about 100 °C to 150 °C, starting nominally around 0 °C.

From the considerations presented so far, a useful figure of merit can be established The amount of waste heat E_{heat} [J] that can be deposited in the active medium of heat capacity c_P (neglecting its temperature dependence for simplicity) over a temperature range ΔT is given by·

$$E_{heat} = m\, c_P\, \Delta T \qquad (2)$$

Using the waste heat parameter X (essentially the quantum defect) the laser output energy over this temperature range is then given by

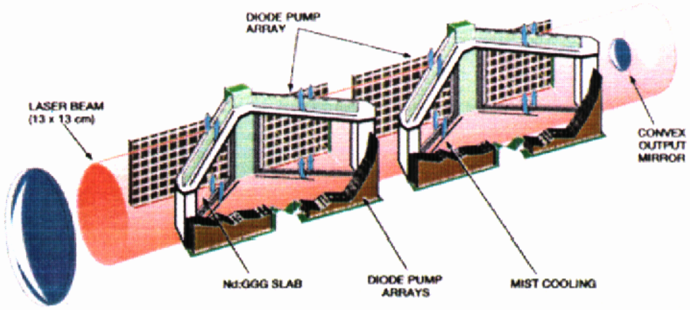
$$E_{out} = \eta_{extr}\, (\rho\, c_P/X)\, \Delta T \qquad (3)$$

There, $\rho * c_P$ is the heat capacity per unit volume (a material parameter), X is a spectroscopy parameter, as is ΔT for optimized systems. The useful temperature range over which the lasing ion can be operated has been discussed above

As usual, many favorable characteristics have to come together for a material to be a good lasing material One or the other isolated favorable characteristic by itself is not sufficient It therefore comes as no surprise that the familiar garnet family of crystalline materials is a favorite for heat capacity lasers as well For Nd^{3+} in GGG, for example, and a ΔT of 100 °C, volume specific energy outputs at ~ 400 J/ cm^3 to 500 J/cm^3 can be expected.

After having reached its upper temperature, the heat capacity laser active medium needs to be cooled back down, i.e. the heat capacity laser needs to be reloaded The governing equations for this phase are very well known [3,9], and shall not be repeated here Now the surface stress is indeed tensile (see also Fig 1), and the requirement to not exceed a maximum stress level limits the cool down times that are achievable To estimate these times, it is important to recognize that factors other than cool down considerations also influence an optimum slab thickness, foremost among them the fill factor (beam area/crystal area under Brewster's angle). The high fill factors (~ 80+%) for operating at high efficiencies generally lead to slab thicknesses in the vicinity of ~ 1cm. This already allows even conservative stress limited cool down times of around 30 sec. It is, however, entirely possible to accommodate optimizations which specifically require even shorter cool down times like 15 sec, leading to thinner slabs.

Fig. 2 shows what one possible embodiment of a heat capacity laser with rapid cool down would look like.



In the example above, we show four out of several Nd^{3+} GGG disks, arranged at alternate Brewster's angle, which constitute the gain elements. The mass of all disks must, of course, be sufficient to store the waste heat of the lasing burst over the specified temperature range. These slabs are sandwiched between clear flow windows, which confine the cooling gas close to the GGG disk, once the cooling phase begins. It is essential to understand that during the lasing phase, no cooling gas flows. This separation of lasing and cooling function in time is one of the pivotal distinction between heat capacity and steady state average power operation, and the very important consequences for the ensuing stresses have been discussed above. The GGG disks are pumped by the diode pump arrays, and the power is extracted by a conventional unstable resonator architecture. To eliminate the effect of residual active medium distortions on the beam, the rear resonator mirror could be envisioned as a deformable mirror, although this is only one of several beam correction implementations possible.

Conclusion:

As heat capacity laser technology matures its pros, cons, and variants will be increasingly better understood, and with it the full spectrum of useful applications will emerge. We believe, that the concept of heat capacity lasing promises to place future solid state lasers, and with it the operational conveniences of all solid state high power laser systems, alongside the well established family of high power gas lasers, thus enriching the options of the user community

References:

[1] A publication with a bıoader and more quantitative discussion of the mateıial sketched in this paper is in pıeparation

[2] "The National Ignition Facility An Overview", ET&R, Dec 1994, UCRL 52000-94-12. Available through LLNL Laser Pıogram, Box 5508, Livermore, CA 94550

[3} An excellent overview of the pertinent technology can be found in "Solid State Laser Engineering", by W. Koechner, Springer, 1996

[4} The origins of the idea are annectotal and undocumented in the open literature, and may date back to the 1970's in several countries, including the US Our own discussions began in 1990/91 duıing the "Defender" pıogıam. The first openly published mateıial we are awaıe of is [5]

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